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THE EFFECTS OF THE DIRECTION OF CONTROL
LOADING ON A ONE-DIMENSIONAL TRACKING TASK

A THESIS

Presented to

The Faculty of the Division of Graduate Studies

By

James Michael Carlin

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In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Industrial Engineering

Georgia Institute of Technology

March, 1980

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Author: Capt James Michael Carlin

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James Michael Carlin
James Michael Carlin

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SUMMARY

Twenty-four subjects were used to assess the effects of the direction of control loading on a one-dimensional closed-loop pursuit tracking task. A zero order (position control) joystick which was free to move only in the fore and aft directions was loaded with either fore, aft, or zero pressure. The track was an irregular sine wave track (random appearing) produced by the addition of five sine waves. It was viewed by the subject on a seventeen inch diagonal black and white television monitor. The video screen presented the subject with a vertical slit through which to view the vertical components of the track movements.

Subjects were instructed to keep an ink pen (also visible on the monitor) superimposed with the track. Control configuration was standard for a joystick in that aft movement of the joystick resulted in an upward movement of the pen tip.

Subjects were randomly assigned to three groups of eight. Each subject performed one familiarization trial and ten scored trials. Group 1 subjects performed five consecutive trials with forward loading and then changed to aft loading. Group 2 started with aft loading and then used forward loading. Group 3 began with a series of five trials with zero loading and were then randomly assigned one-half to forward and one-half to aft loading for the remaining five trials.

Asymmetrical transfer was present between the forward and aft loading conditions. This necessitated restricting the analysis to the first five trials. Loading was not a statistically significant effect on tracking performance as measured by modulus mean error. Trials were highly significant, however, indicating that learning was the dominant effect.

Time series analysis was employed to obtain an estimate of the noise in the response. An AR(2) (second order autoregressive) model provided a good fit to the data (errors). Pooled estimates of noise exhibited a gradual decrease over trials similar to that generated by modulus mean error.

Future studies of this nature should guard more carefully against asymmetrical transfer by restricting groups to the same loading condition throughout the experiment. Learning should be allowed to stabilize. Stress could be induced in order to accentuate the differences between conditions.

CHAPTER I

INTRODUCTION

Background

Modern fighter aircraft flight controls are activated by the pilot through a joystick. Because of heavy loads on the control surfaces, the flight controls are finally actuated by powerful hydraulic actuators. Artificial feel systems of varying complexity are utilized to give some feedback to the pilot to aid in control.

Regardless of the system, virtually all are equipped with thumb-actuated pitch and roll trim. This feature allows the pilot to quickly and easily change the fore and aft or lateral stick force required to control the pitch and roll of the aircraft. The roll trim is usually set and left at a position of near zero lateral force required for level flight. Pitch trim, however, is used throughout flight for the relatively large changes in pitch control required during changes of airspeed and configuration.

During precise tracking tasks such as flying close formation maneuvers, or tracking an air or ground target in an aiming device, many pilots desire to trim the stick forward. A smaller proportion constantly strive for zero pressure in a precise tracking situation. Virtually none trim aft stick pressure in this environment. →

The majority of technical literature that addresses control loading is concerned with friction, inertia, viscous damping, and spring centering (elastic) forces. These are all bi-directional

forces. This study is strictly concerned with uni-directional control loading.

Purpose

The purpose of this study was to determine the effects of the direction of control loading (fore, aft, or zero) on tracking performance, when the target tracked is an irregular (unpredictable) sine wave track.

CHAPTER II

HISTORICAL OVERVIEW

Transfer of Learning

Learning which takes place in a given situation is transferred in a large extent to similar but not identical situations when they are encountered. This is the premise upon which much of our education is based. If this transfer of learning benefits performance in the second situation encountered, it is termed positive transfer. On the other hand, if performance suffers because of the previous learning, the transfer is referred to as negative transfer.

When two conditions A and B are compared using two groups of subjects, it is common practice for one group to perform under condition A and then under B. The second group would perform B first and then A. If the effect on B of performing A first is equal to the effect on A of performing B first, the transfer is symmetrical. However, if one switch results in negative transfer and the other in positive transfer, or if the transfers are in the same direction but not equal, asymmetrical transfer is present.

Asymmetrical transfer has been frequently ignored in tracking studies. It should be noted, that in the presence of asymmetrical transfer, only results of the first trials are valid. The results of the two sets of trials may not be combined (Poulton, 1974, 13-14).

When transfer of learning is asymmetrical, the differences

between experimental conditions are influenced by an unknown extent. There is always a risk of asymmetrical transfer when groups perform under more than one condition and to avoid this risk it is necessary to use a separate group of subjects for each experimental condition (Poulton, 1974, 16-19).

Sine Wave Tracks

Sine waves represent the most common tracking problems encountered in the real world. They present the tracker with constantly changing velocities and accelerations. In contrast, a constantly sloping line (ramp track) would represent a target with a constant angular velocity.

A singular sine wave track is easily learned by a subject and is therefore not suitable except in studies of precognitive tracking. Some subjects will quickly learn the characteristics of the track and "lock in" to frequency and amplitude (Poulton, 1974, 115-117).

It has been shown that a track consisting of a single sine wave can be tracked reasonably well during periods of display blackout for up to three seconds. Practiced subjects will continue to respond at about the correct frequency and amplitude (Poulton, 1974, 229).

Irregular (random appearing) sine wave tracks present a different situation. With track frequencies below about 20 cycles per minute, a subject may continue to respond at about the correct rate, but if the frequencies are higher, he will usually stop responding until the display appears again (Poulton, 1974, 230).

Preview

Changes in performance can occur when preview is increased beyond 0.5 seconds (Poulton, 1974, 187). Targets typically tracked using a joystick present no preview.

Tracking Near the Edge of a Display

When a track approaches the edge of a display, there is obviously only one direction that it may take. For this reason, subjects tend to overshoot reversals in the track less often near the edge than at the center of the display (Poulton, 1974, 25-26).

Upper Limit on Human Response

The upper limit on human response is in the range of 3 corrections per second with most people giving 2 responses per second (Poulton, 1974, 98; Welford, 1976, 89). Sampling rates should be established with this in mind.

Scoring

Overall Measures of Performance

Four of the most commonly used overall measures of performance used in assessing tracking adequacy are:

- 1) Average Error (AE)
- 2) Modulus Mean Error (MME)
- 3) Root Mean Squared Error (RMSE)
- 4) Standard Deviation of the Error (SD)

The equations for these measures are as follows:

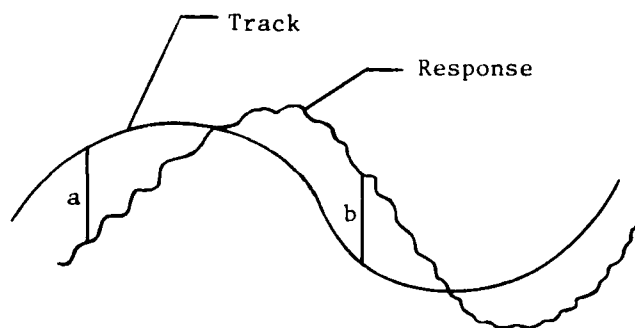
$$AE = \frac{\sum e_i}{n} = \bar{e}$$

$$MME = \frac{\sum |e_i|}{n}$$

$$RMSE = \sqrt{\frac{\sum e_i^2}{n}}$$

$$SD = \sqrt{\frac{\sum (e_i - \bar{e})^2}{n-1}}$$

where e_i is the vertical deviation of the response from the track as measured at n distinct points on the tracking record. Figure 1-1 diagrams the measurements which are recorded to calculate these statistics.



a ~ negative signed error

b ~ positive signed error

Figure 1-1. Error Measurements

Average error in this case has little information because positive and negative errors tend to offset each other and thus average error will usually converge toward zero. It is not a valid measure of lead or lag in this instance because negative error on a rising segment of track is lag, and negative error on a downward bound portion of track is lead. The reverse is true for errors which are positive in sign.

Modulus Mean Error is the average absolute error. This measure has considerable intuitive appeal and is highly representative of tracking adequacy.

Root mean Squared Error is highly correlated with MME. If errors are distributed normally, the correlation is +1.0 and experiments have produced correlations of +.9996 between average RMSE's and MME's. A fairly accurate estimate of average MME can be calculated by multiplying average RMSE by 0.77 (Poulton, 1974, 36).

The difference in the two measures is that RMSE penalizes according to the squared error thereby assigning a heavier penalty to a mixture of large and small errors than it does to a set of average sized errors. MME penalizes only according to the average size of error.

A disadvantage of RMSE is that if the errors are large and always on one side of the track, combining RMSE's underestimates overall error (Poulton, 1974, 37).

Standard Deviation of the Error is the usual unbiased estimate. It, as well as RMSE and MME, are measures of dispersion of the

response about the track (we assume that the mean of the error distribution is zero) (Kelley, 1969). Correlation of MME and SD are presented in Appendix D.

To obtain an estimate of the noise in the response, a measure which has been referred to as the "standard deviation corrected for autocorrelation" (Robinson, 1978) could be used. This statistic is the standard error of the residuals which result from the fitting of a time series model to the response. It can be thought of as an indicator of the variability of the response about itself or the smoothness of the response. Small values of the statistic correspond to a smooth response. This measure will be referred to as the Residual Standard Error (RSE) in this study.

Preliminary Study

A preliminary study was conducted with nine subjects performing one trial with each loading condition, for a total of 27 trials. This experiment demonstrated a lower modulus mean error for forward loading than for aft or zero loading. The stick loading utilized was 4.78 pounds measured at the stick grip center.

CHAPTER III

EXPERIMENTAL DESIGN

Task Description

Subjects were required to perform one-dimensional closed-loop pursuit tracking of an irregular (random appearing) sine wave track using a zero order (position control) joystick that was free to move only fore and aft. (See block diagram Figure 3-1.) Forward movement of the joystick caused the pen to move in the down direction as seen by the subject on the video screen. Aft stick travel resulted in upward pen movement. The track traveled alternately up and down with reversals at irregular (unpredictable) intervals. Subjects attempted to keep the pen tip superimposed with the track.

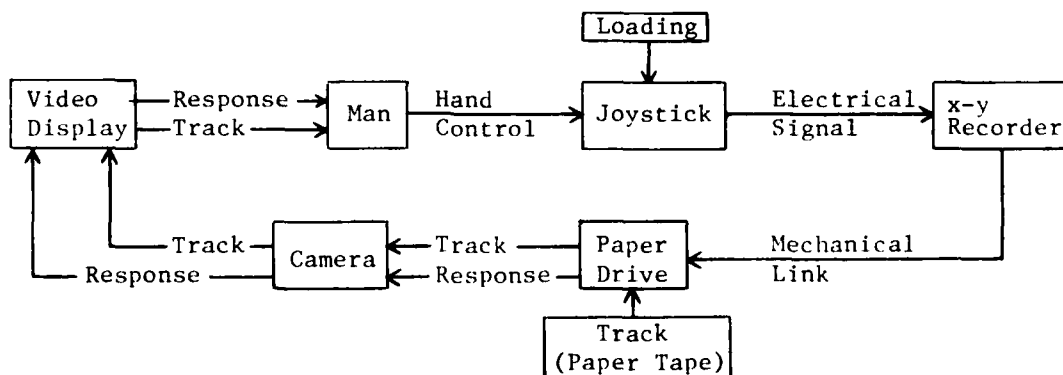


Figure 3-1. Block Diagram of the Closed Loop Pursuit Tracking System

It was undesirable for the tracks to possess easily learned characteristics because tracks with unpredictable traits are more often encountered in reality. A track was selected which is the sum of five

sine waves and is described in detail in Appendix E. In order to reduce the effects of the temptation to anticipate track movements near the display edge, subjects were instructed to not wait on the track but to strive for constant superimposition of the pen and the track. Preview was set at seven millimeters corresponding to 0.28 seconds. Postview was also seven millimeters to present a symmetrical display.

Equipment Description and Set Up

Subjects were seated at a distance of 60 inches from the viewing screen to the eye. The position of the joystick was adjusted so that the neutral position of the joystick corresponded to the knuckles of the right hand when the arm was resting on the arm rest.

The joystick was loaded with 4.78 pounds measured at grip center in either the fore or aft direction for the groups with loading. This loading was chosen because the preliminary study referred to in Chapter II indicated an effect at that stick load. The stick was not loaded for the zero loading condition. Loads were imposed using a 26 pound weight and a pair of pulleys. Friction was negligible in both the loaded and unloaded conditions.

As a convention, forward loading was the condition of load such that when the stick was released it would move full travel away from the subject causing the pen tip to move in the downward direction. The opposite was true for aft loading.

Movement of the joystick caused an electrical signal to

be sent to the x-y recorder via a potentiometer and a power supply. The resulting movements of the recorder were transmitted to the pen by a direct mechanical link. The pen marked the moving track with ink thereby providing a permanent record of a subject's performance.

A closed circuit television camera focused on the track and pen through a 14 millimeter slit. The camera was set to view the full range of track and pen movement and this setting corresponded to a magnification of 1.17 measured at the black and white monitor screen.

Pertinent equipment information is summarized in Table 3-1.

Table 3-1. Equipment Summary

Component	Description
Joystick	0 order (position control)
x-y Recorder	Houston Omnigraphic Model HR-97
Paper Drive	Sanborn Model 154-100B
TV Camera	Panasonic Model WV-1100
TV Monitor	Electrohome Model EVM-1710 Black and White 17" Diagonal Screen

Conduct of Experiment

Twenty-four subjects were recruited and randomly assigned to three groups of eight. The subject was seated at the tracking

station, and the stick position was adjusted for that particular subject. This stick position was recorded in order to expedite future trials. The following standardized instructions were given to each subject on their training session.

Moving the control stick back causes the pen to move up. Similarly, moving the stick forward causes the pen to move down. Note that the joystick is free to move only in the fore and aft directions.

Please move the stick between its limits to get the feel of it, and note the corresponding pen movement on the video screen.

Your task is to keep the pen tip superimposed on the track. The track will move up and down. At first the track will move fairly slowly. After a short period, I will stop the machine in order to change to a higher speed.

Do you have any questions?

At this point, questions were answered, if necessary, and the familiarization trial was run. This trial consisted of tracking a regular sine wave. The track was run at one centimeter per second for one minute and then at 2.5 centimeters per second for one minute providing a total of two minutes familiarization. Each subject utilized the loading condition that his group was to begin with. These first tracks were discarded and were not analyzed.

The next ten trials consisted of tracking the random appearing sine wave track. Each group of subjects performed five consecutive trials with the initial loading condition for the group. After five trials with this initial loading condition, the group which started with forward loading changed to aft loading for five additional trials. The group which started with aft loading was switched to forward loading and the group which began with zero loading was randomly

assigned four to forward loading and four to aft loading. Table 3-2 summarizes this information.

Table 3-2. Order of Experimentation

	Familiarization	1	2	3	4	5	6	7	8	9	10	(Trial #)
Group 1	Forward Load						Aft Load					
Group 2	Aft Load						Forward Load					
Group 3	Zero Load						Four Subjects Forward Load and Four Subjects Aft Load by Random Assignment					

Segregation of the groups in this manner was done to determine if asymmetrical transfer was present between different loading conditions. Because it was expected that loading would somewhat stabilize a subject's tracking (Fogel, 1963, 404; McCormick, 1976, 230), the loaded conditions were concentrated upon and none of the subjects in Group 1 or Group 2 were allowed to perform trials with zero loading.

During a single trial, a subject tracked for 30 seconds. The random appearing sine wave was run at 2.5 centimeters per second. The first 10 seconds were used to allow the subject to stabilize somewhat, and the last 20 seconds of track were scored.

Subjects were not allowed to study the results of their tracking, in order to prevent the possibility of learning the general "shape" of the track and, hence, induce a bias into the results. Strategies and techniques were not suggested to the

subjects; however, they were instructed to try to maintain the pen tip superimposed with the track rather than wait for the track to return to the pen.

Subjects

Subjects were recruited primarily from students of the School of Industrial and Systems Engineering at the Georgia Institute of Technology and those who were enrolled in classes in that department. Since each volunteer was required to run 11 trials (one familiarization and 10 scored) it was necessary to use subjects who regularly frequented the location of the laboratory.

Four of the subjects were pilots (two private pilot fixed wing and two U.S. Army helicopter). None of these subjects had performed pilot duties in the previous 12 months. There was one female subject involved in the study.

Sampling Rate and Performance Measures Chosen

With the upper limit on human response in mind, a sampling rate of five samples per second was utilized in order to capture as much meaningful information as possible without the burden of excessive sampling. Modulus mean error and residual standard error were chosen as overall measures of performance. These statistics are not independent, however, and Appendix D presents the correlation between them.

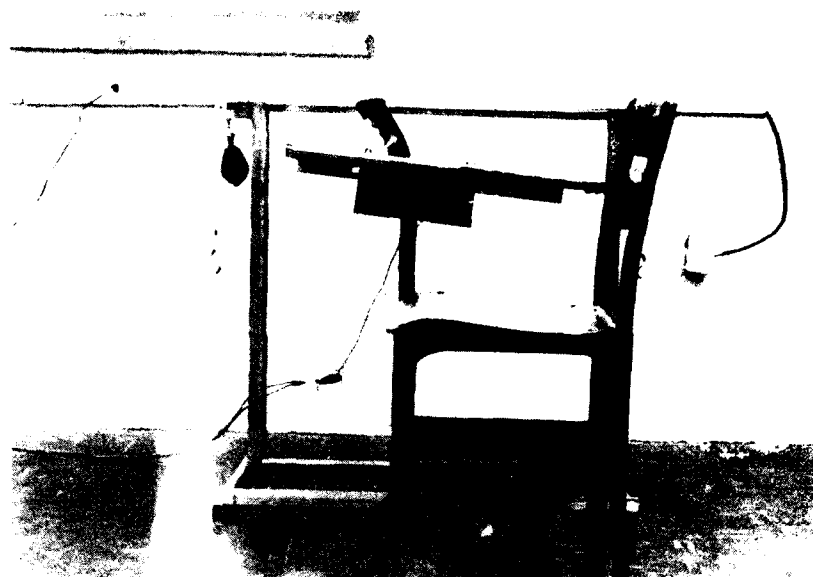


Figure 3-2. Modified School Desk Utilized as Tracking Station

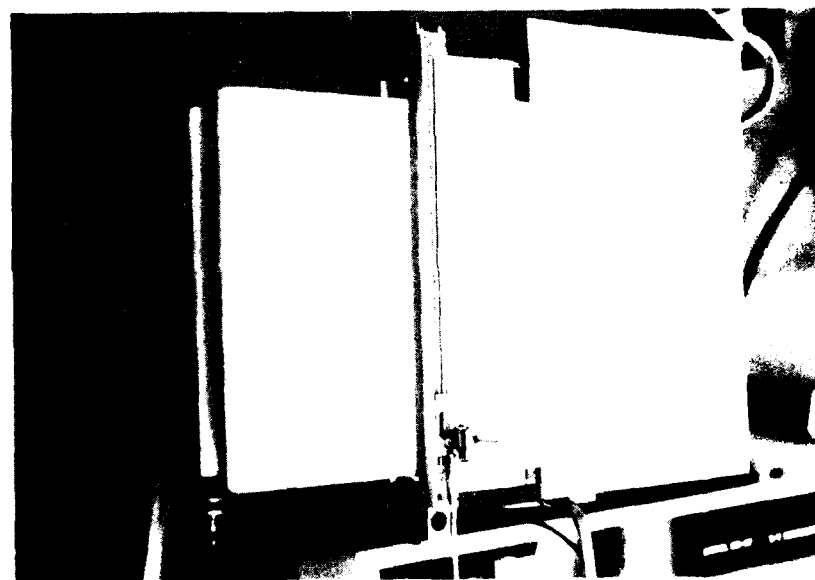


Figure 3-3. Paper Drives with Pen and Paper Track

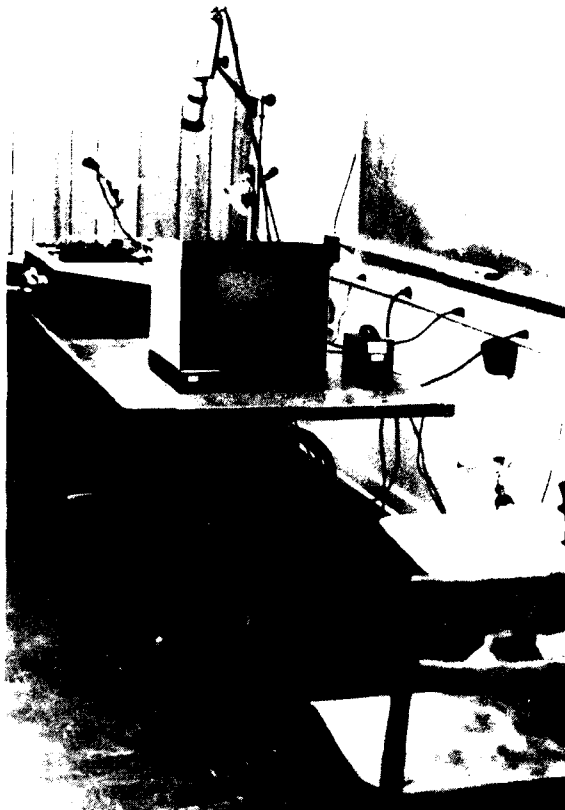


Figure 3-4. Overall Equipment Set Up

CHAPTER IV

DATA ANALYSIS: METHODOLOGY AND RESULTS

All tracks were scored using a Science Accessories Corporation (SAC) Model GP-6-50 sonic digitizer. This equipment consisted of a stylus, an L-frame containing sensors and a microprocessor. Digitizing was accomplished by placing a tracking record overlayed with a clear sheet of plastic within the sensitive area of the L-frame. The plastic sheet was etched with vertical lines equally spaced at five millimeter intervals representing a rate of five samples per second. Successive points were digitized alternating between track and response. Operation was accomplished by actuating the stylus over the point to be digitized. The stylus would emit a supersonic energy pulse (spark) which would be detected by strip-type microphones imbedded in the L-frame. The microprocessor would then compute x and y coordinates of the point and send this information to a data file in the CYBER computer system. A total of 200 points were digitized on each track. This permitted the computation of 100 error measurements with a simple FORTRAN program which calculated the differences between successive pairs of y ordinates and discarded the x values.

The resulting data was then used to calculate modulus mean error and the usual standard deviation for each trial. Time series

analysis was performed using a University of Wisconsin (1970) Box-Jenkins computer program. This analysis concentrated on identification of the correct model and estimation of the model parameters with the standard errors of the residuals being of particular interest.

Modulus Mean Error was pooled over the eight subjects in each group for each of the ten trials. These results are shown in Table A-1 and are plotted in Figure B-1. Simple linear regression equations were formed for Group 1 and Group 2 using pooled MME as the dependent variable and trial number as the independent variable. Three regressions were performed for each group. One through the first five trials, one through the second five, and one through all 10 points.

A procedure to test the equality between sets of coefficients in two linear regressions (Chow, 1960) was used to determine if there was a discontinuity present at five trials where the load changed direction in these two groups.

The general procedure as set forth by Chow follows.

n Observations are used to estimate a regression with p parameters ($p-1$ coefficients plus an intercept).

m Additional observations are available and it is of interest to determine whether or not they are generated by the same regression model as the first observations.

- A Is the residual sum of squares of the dependent variable from the regression using $n+m$ observations and having $n+m-p$ degrees of freedom.
- B Is the residual sum of squares of the dependent variable from the regression using n observations and having $n-p$ degrees of freedom.
- C Is the residual sum of squares of the dependent variable from the regression with m observations having $m-p$ degrees of freedom.

The null hypothesis is that the structure is the same in the two sets. In other words, that a single linear regression gives as good a fit to the data as two separate regressions.

Under this null hypothesis, Chow showed that the statistic

$$R = \frac{(A - B - C)/p}{(B + C)/(n + m - 2p)}$$

will be distributed as F with numerator degrees of freedom equal to p and denominator degrees of freedom equal to $n+m-2p$.

The null hypothesis is rejected when

$$R > F_{\alpha, p, n+m-2p}$$

The regressions gave the results recorded in Table 4-1.

Table 4-1. Linear Regression Results

Group	Trials	Load	Slope	Intercept	SS _{Residual}
1	1-5	Forward	-.0343	.8201	.0286588
1	6-10	Aft	-.0343	.8694	.0735323
1	1-10	Both	-.02683	.7768	.0876186
2	1-5	Aft	-.0506	.9180	.0266708
2	6-10	Forward	-.0258	.7702	.0072528
2	1-10	Both	-.0399	.8447	.1363383

Calculating R for the Group 1 data gives $R = 2.227$ which is not significant at the 0.10 level.

On the other hand the Group 2 data produces, $R = 9.057$ which is significant at the 0.025 level.

For Group 1 the hypothesis of the same structure existing in the two groups of 5 trials cannot be rejected. In Group 2, however, there is a high probability that the two sets do not belong to the same regression and the hypothesis of sameness is rejected at a high level of significance.

These results are evidence of asymmetrical transfer. This means that only the first five trials in each group may be tested for the effects of control loading.

The first five trials in each of the three groups of subjects was then compared on the basis of MME. A BMDP program (2V) was utilized which grouped subjects according to loading condition and considered the effects of the five trials. There

were a total of 118 values of MME available from the first five trials. (Trial number 3 for subject C and trial number 4 for Subject H were lost.) The missing values were estimated by simple linear regression using each subject's four available scores of MME. The BMDP2V output is contained in the ANOVA table in Table 4-2 below.

Table 4-2. ANOVA Table

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	Prob. F Exceeded
Mean	63.39876	1	63.39876	549.74134	-.000
Loading	.10327	2	.05163	.44773	.645
Error	2.42182	21	.11532		
	Sum of Squares	Degrees of Freedom	Mean Square	F	Prob. F Exceeded
Trials	.64769	4	.16192	8.78794	.000
Trial Loading Interaction	.12851	8	.01606	.87185	.544
Error	1.54775	84	.01843		

Inspection of these results indicate that loading did not have a significant effect on performance as measured by MME; trials were highly significant, however. Learning appears to be the major factor affecting tracking proficiency during the first five trials.

The error degrees of freedom should be reduced because of the two missing values that were estimated. However, the results of the analysis of variance would remain practically unchanged.

Time series analysis was necessary to obtain estimates of

the noise in the response. This analysis was performed in three stages: (1) Model Identification, (2) Estimation of Parameters, and (3) Diagnosis of Model Adequacy. The first stage was accomplished by choosing one trial at random from each of the 24 subjects for examination using the Box-Jenkins identification program. Correlograms of both the autocorrelation function (ACF) and the partial autocorrelation function (PACF) were produced by this program. The ACF plots exhibited a mixture of damped exponentials and damped sinusoidal patterns. The plots of PACF had spikes at lags one and two which exceeded two standard error limits. These patterns are characteristic of an autoregressive process of order two (an AR(2) model). If we let e_t denote the error at time t and a_t a random shock at time t , the AR(2) model can be written

$$(e_t - \mu) = \phi_1 (e_{t-1} - \mu) + \phi_2 (e_{t-2} - \mu) + a_t$$

where ϕ_1 and ϕ_2 are the two autoregressive parameters and μ is the mean of the errors. The model hypothesizes that the error at time t is dependent on the error at time $t-1$ and at time $t-2$ plus some random shock. If the average error is zero the model becomes,

$$e_t = \phi_1 e_{t-1} + \phi_2 e_{t-2} + a_t \quad .$$

Using the AR(2) as a tentative model, the parameter estimation phase of the Box-Jenkins computer routine was run on

each of the 238 trials with 100 observations per trial. The estimation phase uses a special non-linear program to obtain estimates of the autoregressive parameters. It then fits the model to the data and calculates as well as plots residuals. The ACF and PACF of the residuals are then calculated and plotted in correlograms. If model fit is adequate, these correlograms should exhibit white noise behavior and there should not be a significant spike (beyond two standard error limits) at lag one in either of the plots. Residual plots should also exhibit no structure.

An approximate lack of fit test (Box and Jenkins, 1976 290-293) can be performed with the statistic

$$Q = n \sum_{k=1}^K r_k^2$$

where n = the number of observations used to fit the model, r_k = the estimated autocorrelation of the residuals lag k and K = the number of autocorrelations used to calculate Q (usually $K = n/20$ or $n/25$). If the fitted model is appropriate, Q is distributed as Chi Square with degrees of freedom equal to K less the number of parameters estimated.

The parameters estimated were ϕ_1 , ϕ_2 , and μ the mean of the process. These parameters were estimated along with 95 percent confidence bounds on each of them. Only thirteen (5.46%) values of the mean were significantly different than zero. That is the

95% confidence interval on estimates of the mean included the value of zero in all but 5.46% of the series. Similarly, every estimate of ϕ_1 , was significantly different than zero and only four estimates (1.7%) of ϕ_2 were not significantly different than zero. These results imply that parameters of the AR(2) model with zero mean are generally significant at the 5% level when fit to the tracking errors of this study.

All three of these diagnostic checks are part of the output of the estimation phase of the program. The residual plots showed no readily discernible patterns. Only a small percentage of the results showed the possibility of violating white noise requirements in the correlograms and these generally had inflated values of Q.

Among 238 separate time series analyses it is reasonable to assume that some of them will exhibit an invalid fit because of random chance. A Chi Square Goodness of Fit test was performed on the 238 Q statistics.

It was hypothesized that the Q statistics are distributed as Chi Square with 22 degrees of freedom. Class intervals were formed based on percentage points available in a Chi Square tabulation in (Box and Jenkins, 1976).

The first three class intervals were combined to obtain an expected frequency of at least five. The same was done for the last four class intervals. This resulted in 10 class intervals.

Table 4-3. Distribution of Q Statistics by Class Intervals

Class Interval	p	Expected	Observed
≤ 8.64	.005	1.19	3
$8.64 < Q \leq 9.54$	.005	1.19	3
$9.54 < Q \leq 11.0$	.015	3.57	3
$11.0 < Q \leq 12.3$	.025	5.95	6
$12.3 < Q \leq 14.0$	.05	11.9	14
$14.0 < Q \leq 17.2$	.15	35.7	36
$17.2 < Q \leq 21.3$	.25	59.5	65
$21.3 < Q \leq 26.0$	.25	59.5	49
$26.0 < Q \leq 30.8$	.15	35.7	32
$30.8 < Q \leq 33.9$	.05	11.9	14
$33.9 < Q \leq 36.8$	.025	5.95	6
$36.8 < Q \leq 40.3$	.015	3.57	3
$40.3 < Q \leq 42.8$	.005	1.19	3
$42.8 < Q \leq 48.3$	.004	.952	1
$48.3 < Q$	.001	.238	0

The test statistic

$$\chi_0^2 = \sum_{i=1}^{10} \frac{(O_i - E_i)^2}{E_i} = 5.24$$

is not significant when compared to a Chi Square random variable with 9 degrees of freedom

$$P(\chi_9^2 > 5.24) = 0.81$$

The histogram in this chapter also shows a good fit of the Q statistics to the theoretical Chi Square distribution.

At this point the AR(2) model with zero mean was concluded to be a good fit to the response and was chosen as the final model.

The estimation stage of the Box-Jenkins program provides estimates of the standard errors of the residuals. These can be considered a measure which is inversely proportional to the "smoothness" of the response. Responsibility for the noise rests with such factors as equipment jitter, muscle tremor and certain nonlinear strategies that the subject may have been using. A graph of these standard errors is included in Appendix B. It evidences no discernible difference with control loading but rather a gradual improvement over the course of 10 trials.

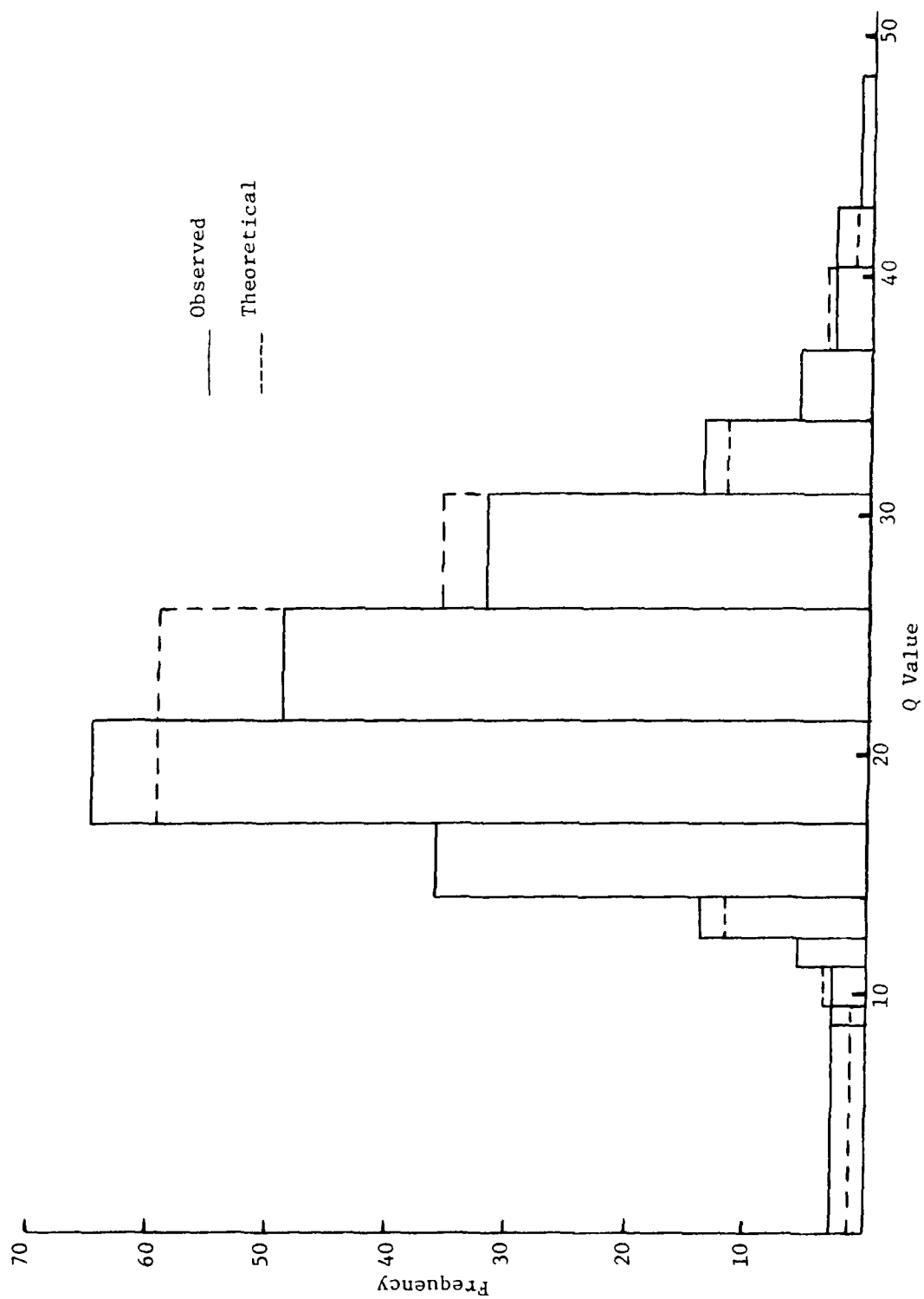


Figure 4-1. Histogram of 238 Q Statistics

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Asymmetrical transfer exists between forward loading and aft loading. This is evidenced by the regressions of MME against trials. Group 1 experienced a change in intercept but no change in slope when transferring from forward loading to aft loading. Group 2 regressions produced both a change in slope and intercept when they switched from an aft load condition to a forward load condition. Chow's procedure showed that a single regression through all ten trials was as good a fit as two separate regressions on five trials each for Group 1 data. For Group 2, however, the opposite was true; a better fit was obtained with two regressions.

The presence of asymmetrical transfer means that only the results of the first five trials may be analyzed for the effects of the direction of control loading on tracking performance.

The effects of control loading are not statistically significant during these first five trials. The effect of trials is highly significant, indicating that learning is the dominant effect. Inspection of a plot of pooled MME against trial number indicates that learning has not leveled off even by trial number 10.

An AR(2) model adequately provides a good fit to the data for the purpose of estimating the noise in the response. This

model is valid under the experimental conditions of this study and is subject to change if any of the track or control characteristics are altered. Sampling rate should also have an effect on the selection of an appropriate time series model.

Recommendations

When similar studies are conducted in the future, groups should remain with one loading condition. Learning should be allowed to stabilize. This could be accomplished by having the subject perform at least ten trials during a training phase, after which scored trials would be accomplished. The initial eight to ten trails need not be scored if the purpose was to assess the effects of control loading, as in this study.

Conditions which exhibit negligible differences under laboratory conditions are nearly always differentiated more significantly under stress conditions (Poulton, 1974, 22). If a stress situation is induced into the trials it could be beneficial in that it may magnify the differences between groups.

APPENDIX A

POOLED DATA

Table A-1. Pooled Modulus Mean Error

Trial	Group 1	Group 2	Group 3		
1	.800	.885	.878		
2	.799	.790	.684		
3	.603	.771	.693		
4	.712	.716	.593		
5	.672	.669	.633	Gp 3 (FWD)	Gp 3 (Aft)
6	.696	.625		.627	.562
7	.635	.578		.584	.625
8	.508	.554		.551	.524
9	.588	.554		.530	.524
10	.548	.508		.512	.593

Table A-2. Pooled Standard Deviations (Usual Unbiased Statistic)

Trial	Group 1	Group 2	Group 3		
1	1.18	1.27	1.22		
2	1.17	1.16	.96		
3	.86	1.13	.97		
4	.98	.99	.83		
5	.94	.99	.87	Gp 3 (FWD)	Gp 3 (AFT)
6	1.01	.85		.89	.76
7	.89	.84		.78	.89
8	.71	.78		.73	.70
9	.80	.79		.79	.78
10	.79	.70		.70	.83

Table A-3. Pooled Standard Error of the Residuals from AR(2) Model

Trial	Group 1	Group 2	Group 3		
1	.567	.588	.633		
2	.558	.574	.540		
3	.491	.588	.523		
4	.542	.514	.499		
5	.499	.501	.520	Gp 3 (FWD)	Gp 3 (AFT)
6	.520	.486		.627	.435
7	.495	.454		.448	.484
8	.412	.440		.435	.453
9	.430	.447		.426	.415
10	.400	.420		.460	.414

APPENDIX B

PLOTS OF POOLED STATISTICS

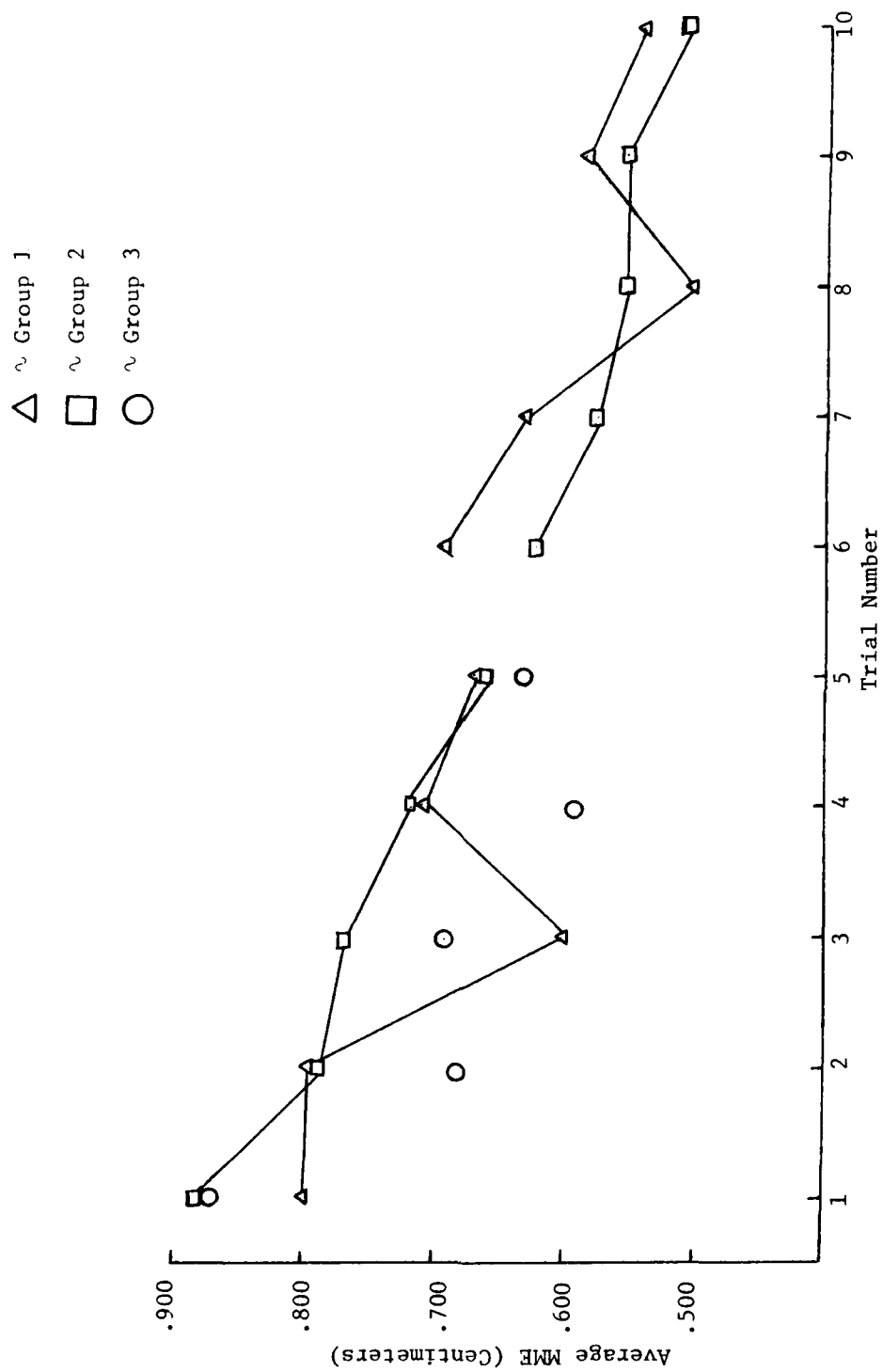


Figure B-1. Pooled Modulus Mean Error Versus Trial Number

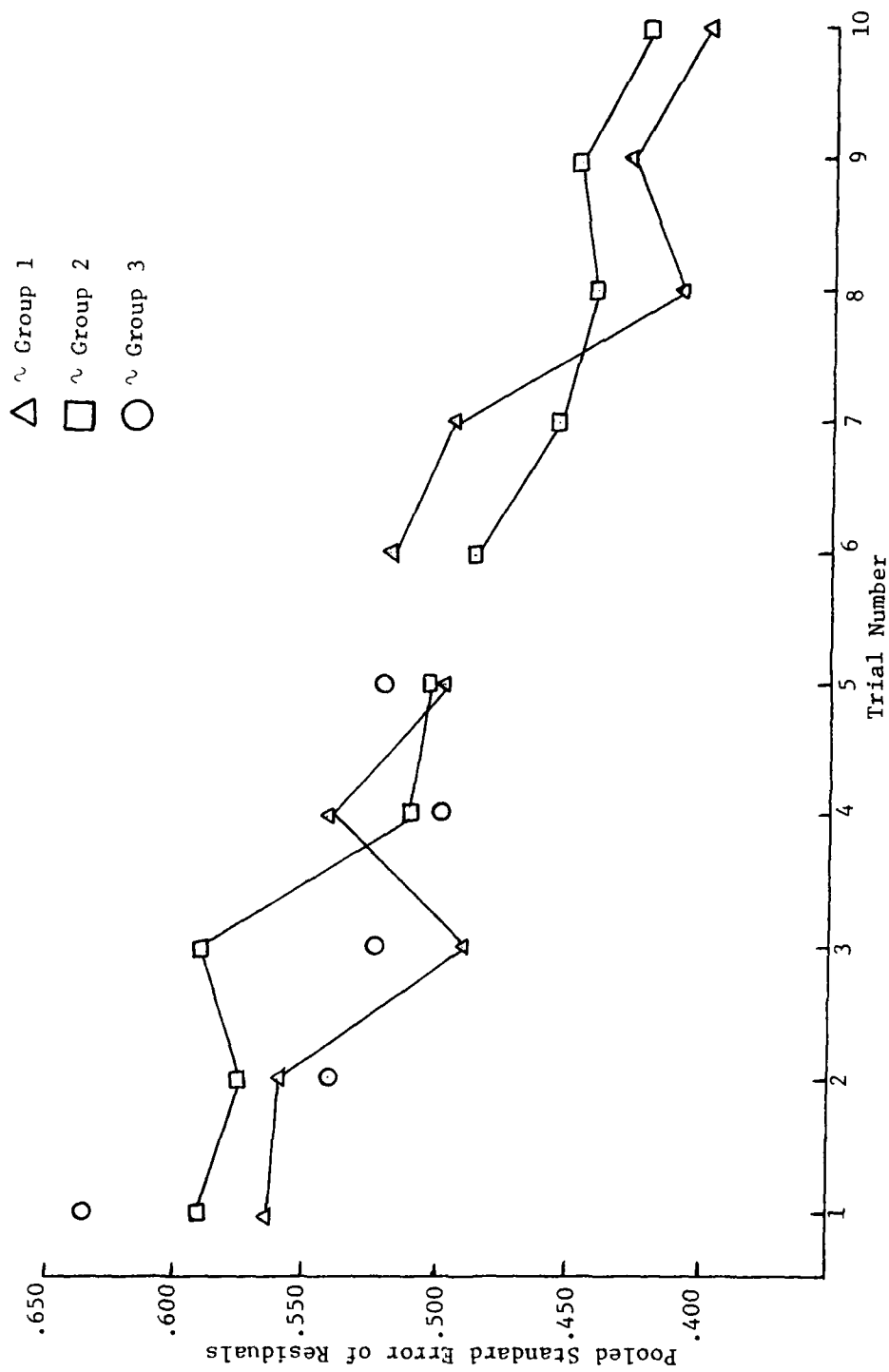


Figure B-2. Pooled Standard Errors of the Residuals Versus Trial Number

APPENDIX C

SUBJECT DEMOGRAPHIC DATA

Table C-1. Subject Demographic Data

Subject	Ht.	Wt.	Age	Occupation
A	5'-11"	180	28	I.E. Grad Student
B	5'-7.5"	158	25	I.E. Grad Student
C	6'-5"	227	28	I.E. Grad Student (Private pilot)
D	6'-2"	175	23	I.E. Grad Student
E	5'-11"	160	40	I.E. Professor
F	5'-11"	156	23	I.E. Undergrad
G	5'-8.5"	150	21	I.E. Undergrad
H	6'-2"	160	28	M.E. Grad Student
I	5'-10.5"	190	44	I.E. Grad Student
J	5'-11"	180	32	I.E. Grad Student
K	5'-10"	160	28	I.E. Grad Student (A.F. Navigator)
L	5'-8"	155	20	I.E. Undergrad
M	5'-8"	140	31	I.E. Grad Student (Army Helicopter
N	6'-0"	180	31	" " " Pilot, Both M & N)
O	6'-2.5"	175	23	I.E. Undergrad
P	5'-9"	168	25	I.E. Grad Student
Q	5'-8.5"	168	27	I.E. Grad Student
R	6'-1.5"	192	27	I.E. Grad Student (Private Pilot)
S	5'-10.5"	155	25	I.E. Grad Student
T	5'-6"	130	29	I.E. Grad Student
U	5'-7.5"	165	33	I.E. Professor
V	5'-10.75"	162	22	I.E. Undergrad
W	5'-10"	175	24	I.E. Grad Student
X	5'-4"	115	21	EE Grad Student (Female)

APPENDIX D

CORRELATION OF STATISTICS

Modulus Mean Error (MME) and Standard Deviation (SD)

It has been shown (Montgomery and Johnson, 1976) that

$$MME = \sqrt{\frac{2}{\pi}} SD \approx 0.8SD$$

where the errors are assumed distributed normally with constant mean and variance $(SD)^2$. (The relationship holds well for nonnormal errors also.)

Modulus Mean Error and Standard Error of Residuals (σ_a)

For the AR(2) model the relationship between SD and MME is

$$SD^2 = \frac{1 - \phi_2}{1 + \phi_2} \frac{\sigma_a^2}{\{(1 - \phi_2)^2 - \phi_1^2\}} = \frac{\pi}{2} MME^2$$

(Box and Jenkins, 1976).

It follows algebraically that

$$\sigma_a^2 = \{(1 - \phi_2)^2 - \phi_1^2\} \frac{1 + \phi_2}{1 - \phi_2} \frac{\pi}{2} MME^2$$

APPENDIX E

DESCRIPTION OF TRACKS

The regular sine wave used for familiarization was a single sine wave with

$$\begin{aligned}\text{period} &= 40.0 \text{ cm. and} \\ \text{amplitude} &= 6.325 \text{ cm.}\end{aligned}$$

This track was driven at one centimeter per second for one minute and at 2.5 centimeters per second for the last minute of the familiarization.

The irregular (random appearing) sine wave track was produced by summing five sine waves. The distance before repetition of the pattern was 79.8 centimeters and the maximum vertical travel of the track was 17.0 centimeters. There were 17 reversals in 79.8 centimeters. If we let

X = horizontal distance in centimeters

$R = X/6.3050282539$ (radians) and

Y = vertical distance in centimeters

then the equation for the track is

$$Y = 2.540005 \{ \sin(5R) + \sin(3.5R) + \sin(2.5R) + \sin(R) + \sin(0.5R) \} .$$

The computer programs which were used to plot these tracks on the VERSATEC plotter at the Georgia Tech Computing Center are included for reference on the following pages.

```
PROGRAM FLT (INPUT,OUTPUT)
DIMENSION X(3002),Y(3002),IBUF(512)
X(1)=0
Y(1)=0
D=2*3.1415926/299
DO 50 I=2,3000
X(I)=D*(I-1)
Y(I)=SIN(X(I))
50 CONTINUE
CALL PLOTS (IBUF,512,8,00)
CALL PLOTMX(200.)
CALL SCALE(X,200.,3000,1)
CALL SCALE(Y,8.,3000,1)
CALL LINE(X,Y,3000,1,0,0)
CALL PLOT(0.,0.,999)
STOP
END
```

Figure E-1. Single Sine Wave Program

This program generates the single sine wave track on the VERSATEC plotter at the Georgia Institute of Technology computing center.

```
PROGRAM PLT (INPUT,OUTPUT)
DIMENSION X(3002),Y(3002),IBUF(512)
X(1)=0
Y(1)=0
D=2*3.1415926/299
DO 50 I=2,3000
X(I)=D*(I-1)
Y(I)=SIN(5*X(I))+SIN(3.5*X(I))+SIN(2.5*X(I))
1+SIN(X(I))+SIN(0.5*X(I))
50 CONTINUE
CALL PLOTS (IBUF,512,8,00)
CALL PLOTMX(200.)
CALL SCALE(X,200.,3000,1)
CALL SCALE(Y,8.,3000,1)
CALL LINE(X,Y,3000,1,0,0)
CALL PLOT(0.,0.,999)
STOP
END
```

Figure E-2. Irregular Sine Wave Program

This program generates the irregular sine wave track on the VERSATEC plotter at the Georgia Institute of Technology computing center.

APPENDIX F

INDIVIDUAL SUBJECT AND TRIAL STATISTICS

The abbreviations in the tables of this section are as follows:

MME = Modulus Mean Error

SD = Standard Deviation (usual unbiased form)

SER = Standard Error of the Residuals (from AR(2) model)

Q = Chi Square Lack of Fit Statistic

ϕ_1 = First Order Autoregressive Parameter

ϕ_2 = Second Order Autoregressive Parameter

Table F-1. Subject A Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.497	.697	.478	14.972	.94457	-.37509
2	.543	.619	.432	33.749	.83898	-.20693
3	.416	.573	.365	22.543	1.0399	-.46982
4	.549	.791	.450	5.5997	1.0551	-.30179
5	.575	.726	.360	33.766	1.2098	-.44344
6	.631	.924	.519	22.485	1.1566	-.49854
7	.578	.805	.355	28.197	1.2774	-.43045
8	.396	.505	.378	13.54	.77394	-.1784
9	.434	.570	.320	12.117	1.1482	-.53804
10	.414	.594	.329	30.384	1.1739	-.51557

Table F-2. Subject B Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.655	.905	.404	16.948	1.3353	-.49269
2	.798	1.022	.389	20.003	1.2909	-.49161
3	.652	.930	.415	21.012	1.1748	-.33028
4	.719	1.043	.401	14.474	1.3915	-.57158
5	.482	.623	.389	10.675	1.0399	-.38572
6	.659	.868	.487	18.858	1.1131	-.40306
7	.588	.796	.331	23.068	1.3083	-.4792
8	.567	.792	.392	14.492	1.2117	-.43733
9	.561	.702	.399	22.173	1.0683	-.30736
10	.390	.518	.338	24.348	.94772	-.29833

Table F-3. Subject C Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	1.156	1.377	.611	21.651	1.2733	-.48886
2	1.073	1.460	.522	19.716	1.3662	-.49337
3	-	-	-	-	-	-
4	.673	.872	.473	16.658	1.1594	-.43748
5	.978	1.289	.498	18.18	1.3078	-.46732
6	.969	1.357	.435	21.031	1.485	-.6225
7	.598	.797	.409	21.906	1.1819	-.42011
8	.597	.740	.471	24.195	1.0477	-.50152
9	.594	.765	.397	42.215	1.1999	-.46349
10	.760	.928	.463	17.525	1.2159	-.45574

Table F-4. Subject D Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	1.344	1.876	.715	17.231	1.2827	-.43322
2	1.140	1.585	.763	24.692	1.2575	-.49929
3	.743	.984	.651	15.688	.92393	-.43539
4	1.058	1.341	.711	15.590	1.2005	-.49536
5	.911	1.215	.573	22.166	1.283	-.54373
6	.866	1.208	.682	32.093	1.1590	-.53511
7	.867	1.174	.656	19.83	1.1666	-.60079
8	.670	.873	.503	14.836	1.1294	-.61459
9	.989	1.258	.647	11.79	1.2177	-.50503
10	.609	.774	.438	11.767	1.1026	-.39540

Table F-5. Subject E Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.689	1.161	.556	16.407	1.252	-.48234
2	.757	1.200	.546	20.864	1.2376	-.4278
3	.723	1.004	.490	32.794	1.2107	-.43135
4	.677	.905	.619	17.174	.95882	.42306
5	.668	.882	.539	21.563	1.0816	-.48611
6	.516	.662	.489	18.398	.82914	-.24345
7	.643	.866	.455	28.303	1.1898	-.47745
8	.478	.718	.403	38.431	1.1267	-.42434
9	.503	.700	.372	22.402	1.2005	-.53345
10	.409	.590	.348	28.059	.98527	-.28843

Table F-6. Subject F Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	1.011	1.424	.700	36.436	1.235	-.47436
2	1.008	1.534	.630	15.314	1.350	-.53995
3	.842	1.161	.645	17.305	1.1427	-.47547
4	.544	.793	.568	27.038	.84579	-.21608
5	.917	1.260	.696	18.432	1.0335	-.27397
6	.889	1.328	.590	17.957	1.2256	-.38857
7	.738	1.019	.513	42.761	1.1793	-.41119
8	.701	.983	.429	19.618	1.281	-.46378
9	.696	.993	.436	19.26	1.2912	-.48449
10	1.035	1.432	.505	27.85	1.3965	-.53009

Table F-7. Subject G Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.523	.746	.471	15.507	1.0341	-.41641
2	.605	.803	.508	18.164	.95761	-.25197
3	.431	.558	.319	22.153	1.0012	-.25054
4	.766	.999	.511	12.538	1.1486	-.36632
5	.495	.664	.444	32.237	.99493	-.42626
6	.581	.832	.499	26.52	1.0962	-.53543
7	.610	.917	.692	12.925	.83232	-.34646
8	.390	.505	.401	13.465	.74791	-.35355
9	.422	.513	.358	22.396	.87723	-.32697
10	.426	.547	.387	18.321	.88639	-.2725

Table F-8. Subject H Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.526	.683	.520	24.204	.79596	-.45727
2	.470	.696	.586	22.931	.5927	-.37291
3	.415	.578	.450	30.02	.77719	-.39015
4	-	-	-	-	-	-
5	.346	.521	.405	14.821	.76278	-.23201
6	.460	.572	.411	17.894	.84775	-.27569
7	.456	.599	.425	20.592	.88729	-.30753
8	.266	.356	.285	28.65	.72078	-.31434
9	.505	.670	.430	24.489	1.0001	-.49745
10	.342	.462	.356	16.976	.79898	-.35819

Table F-9. Subject I Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.831	1.227	.595	16.275	1.2186	-.43274
2	.736	1.174	.580	19.484	1.1391	-.32631
3	1.103	1.729	.921	9.3327	1.1632	-.41926
4	.703	.927	.577	22.068	1.065	-.48038
5	.935	1.465	.795	13.793	.88836	-.29261
6	.644	.897	.664	11.906	.85762	-.37610
7	.701	1.107	.598	14.08	1.1164	-.35413
8	.777	1.030	.532	19.883	.99339	-.15775
9	.575	.812	.551	18.974	.95775	-.44734
10	.502	.625	.412	13.564	.9423	-.35672

Table F-10. Subject J Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.787	1.047	.557	27.277	1.1596	-.42886
2	.545	.696	.512	25.779	.85979	-.36523
3	.666	.858	.579	25.206	.95569	-.48422
4	.702	.946	.523	27.329	1.1474	-.42675
5	.481	.670	.361	28.452	1.078	-.53322
6	.588	.768	.523	21.979	.96689	-.44007
7	.465	.624	.376	8.6581	1.094	-.45583
8	.392	.510	.373	18.603	.86118	-.34638
9	.370	.506	.360	21.256	.90716	-.45414
10	.453	.599	.364	24.599	1.0774	-.57908

Table F-11. Subject K Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	1.335	1.787	.864	11.63	1.2495	-.48650
2	.777	1.084	.614	18.236	1.0658	-.42695
3	.782	1.046	.528	29.228	1.1307	-.33218
4	.779	1.082	.564	32.053	1.1525	-.38336
5	.843	1.101	.556	14.792	1.2046	-.41294
6	.716	.946	.547	25.718	1.1022	-.45500
7	.730	1.011	.544	20.75	1.1038	-.3323
8	.603	.859	.533	19.035	1.0291	-.38779
9	.553	.705	.460	18.963	.98484	-.34855
10	.683	.900	.550	13.813	1.0719	-.46752

Table F-12. Subject L Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.987	1.396	.573	25.264	1.3205	-.49786
2	.798	1.198	.654	14.277	1.0908	-.32172
3	.681	.978	.480	18.364	1.1704	-.3849
4	.651	.881	.455	24.599	1.1298	-.33566
5	.566	.818	.411	30.044	1.1991	-.43492
6	.582	.794	.427	27.036	1.0932	-.31543
7	.534	.745	.374	18.917	1.2335	-.49193
8	.506	.680	.433	25.741	.96052	-.26691
9	.528	.731	.374	19.625	1.1908	-.44284
10	.497	.717	.391	13.296	1.1546	-.43971

Table F-13. Subject M Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.810	1.019	.408	14.373	1.3306	-.49046
2	.653	.976	.427	33.885	1.2158	-.37368
3	.715	1.050	.457	15.201	1.289	-.4812
4	.674	1.007	.415	17.402	1.3327	-.50955
5	.625	.939	.357	25.199	1.3728	-.52516
6	.615	.831	.430	17.916	1.0986	-.2960
7	.480	.622	.392	12.333	.95836	-.24855
8	.476	.635	.414	22.571	.97007	-.32693
9	.408	.550	.357	25.136	.99585	-.36377
10	.459	.644	.427	6.9251	.93849	-.28257

Table F-14. Subject N Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.974	1.476	.549	12.54	1.3374	-.50207
2	1.283	1.726	.566	22.543	1.461	-.58962
3	.782	1.198	.496	34.914	1.2826	-.50050
4	.717	.969	.425	42.655	1.2851	-.48531
5	.701	1.010	.432	19.695	1.3271	-.54720
6	.691	.899	.390	21.976	1.3418	-.5767
7	.647	1.097	.392	20.658	1.3754	-.50596
8	.586	.949	.387	27.812	1.296	-.47200
9	.843	1.163	.513	17.278	1.3186	-.54647
10	.529	.809	.404	19.57	1.2235	-.50088

Table F-15. Subject O Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.518	.694	.488	21.01	.87504	-.27619
2	.690	1.013	.655	26.448	1.0129	-.35707
3	.667	.840	.633	27.68	.78681	-.38605
4	.614	.830	.596	18.74	.89594	-.42206
5	.504	.674	.513	28.676	.72307	-.53606
6	.461	.593	.480	15.187	.63611	-.45486
7	.552	.705	.525	16.327	.8340	-.41058
8	.448	.558	.412	27.825	.77707	-.53272
9	.508	.612	.439	18.944	.83656	-.45238
10	.408	.545	.387	18.923	.89642	-.36080

Table F-16. Subject P Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.840	1.187	.566	22.96	1.1921	-.38566
2	.838	1.122	.550	9.1066	1.1199	-.29716
3	.771	1.052	.468	20.256	1.2135	-.39246
4	.889	1.197	.525	22.486	1.3097	-.50738
5	.700	.987	.437	14.952	1.1648	-.39561
6	.705	1.038	.358	17.461	1.4298	-.59276
7	.516	.639	.365	26.541	1.0613	-.31128
8	.647	.833	.407	14.757	1.2960	-.52655
9	.644	1.013	.481	14.018	1.2584	-.48528
10	.533	.707	.401	15.387	1.0996	-.35443

Table F-17. Subject Q Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	1.063	1.451	.594	17.753	1.2737	-.38643
2	.670	.879	.447	35.282	1.1349	-.36782
3	.828	1.066	.608	24.603	1.0187	-.25245
4	.682	.871	.489	23.821	1.1358	-.44256
5	.653	.926	.532	15.851	1.1183	-.43303
6	.517	.709	.452	19.001	.99913	-.35286
7	.641	.848	.477	16.222	1.0736	-.31787
8	.664	.882	.487	18.933	1.1517	-.47075
9	.517	.774	.430	16.739	1.2663	-.64464
10	.545	.758	.451	23.098	1.0792	-.39621

Table F-18. Subject R Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.699	.902	.492	32.998	1.2202	-.53756
2	.839	1.211	.460	28.108	1.3739	-.53209
3	.553	.734	.545	19.085	.82920	-.47438
4	.453	.622	.456	14.704	.8717	-.43962
5	.676	.861	.682	18.717	.71673	-.43500
6	.919	1.285	.979	10.621	.75292	-.52704
7	.519	.692	.507	15.462	.82295	-.51882
8	.469	.572	.432	27.647	.80151	-.40208
9	.513	.726	.450	19.767	1.0520	-.55289
10	.420	.544	.435	23.343	.73908	-.37643

Table F-19. Subject S Statistics

Trial	MME	SD	SER	Q	$\hat{\phi}_1$	$\hat{\phi}_2$
1	.838	1.124	.798	20.774	.83164	-.41195
2	.603	.731	.524	20.844	.78923	-.36645
3	.451	.589	.391	30.679	.87105	-.17868
4	.710	.942	.639	6.5444	.93513	-.30798
5	.502	.698	.550	21.703	.82539	-.32430
6	.512	.655	.443	10.129	.95755	-.42388
7	.471	.593	.408	22.849	.94334	-.46066
8	.451	.591	.458	32.569	.69051	-.20899
9	.416	.523	.382	17.478	.78333	-.49869
10	.579	.710	.465	23.773	.99345	-.38378

Table F-20. Subject T Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	1.078	1.508	.498	36.011	1.3992	-.52902
2	.802	1.121	.491	33.214	1.3138	-.51416
3	.762	1.114	.485	32.382	1.2684	-.43686
4	.470	.673	.403	25.358	1.0857	-.44691
5	.679	.964	.474	27.129	1.2385	-.4922
6	.433	.566	.378	41.998	.96869	-.38457
7	.790	1.094	.534	17.937	1.1859	-.39958
8	.556	.720	.456	30.896	.97162	-.27038
9	.459	.673	.398	29.535	1.0774	-.39431
10	.434	.567	.341	24.362	.95861	-.31486

Table F-21. Subject U Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.826	1.220	.608	18.864	1.1207	-.32501
2	.560	.785	.518	26.992	.9889	-.39084
3	.638	1.095	.711	15.669	.92807	-.22642
4	.510	.720	.486	21.278	.95784	-.37489
5	.471	.627	.400	27.561	1.0198	-.42643
6	.548	.760	.368	12.532	1.1593	-.36018
7	.758	1.074	.535	19.521	1.1768	-.39008
8	.431	.637	.348	11.539	1.1330	-.3912
9	.546	.743	.391	39.355	1.1999	-.49120
10	.575	.855	.394	18.484	1.3513	-.61039

Table F-22. Subject V Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.873	1.141	.791	37.682	.90789	-.43414
2	.810	1.163	.802	22.575	.92422	-.31999
3	.592	.773	.509	30.350	.96755	-.3400
4	.551	.702	.470	18.192	.97803	-.49425
5	.592	.740	.505	20.802	.96173	-.42692
6	.568	.745	.509	19.934	.95898	-.43695
7	.570	.703	.447	21.357	1.0298	-.36574
8	.624	.830	.457	27.655	1.0643	-.31008
9	.544	.731	.451	21.416	.9940	-.33574
10	.628	.841	.539	14.349	1.0014	-.35837

Table F-23. Subject W Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.854	1.166	.610	27.13	1.119	-.32749
2	.598	.785	.474	28.777	1.0674	-.40466
3	.622	.784	.369	21.556	1.2192	-.46021
4	.519	.697	.407	14.148	.95020	-.1691
5	.668	.877	.473	13.524	1.1808	-.47913
6	.504	.662	.389	31.445	1.1097	-.4733
7	.604	.847	.345	12.488	1.3524	-.55134
8	.446	.591	.352	22.809	1.1749	-.54733
9	.544	.926	.369	22.47	1.3973	-.50161
10	.454	.613	.405	15.78	.99049	-.42892

Table F-24. Subject X Statistics

Trial	MME	SD	SER	Q	ϕ_1	ϕ_2
1	.793	1.152	.599	32.752	1.1947	-.4652
2	.592	.868	.517	20.294	1.0169	-.29332
3	1.094	1.387	.481	34.812	1.4416	-.59747
4	.849	1.216	.596	22.014	1.1825	-.38043
5	.819	1.168	.502	34.705	1.2196	-.36617
6	.753	.989	.532	19.192	1.1142	-.34712
7	.480	.664	.445	18.905	.98567	-.40539
8	.659	.817	.532	13.86	.9744	-.31852
9	.673	1.063	.482	16.319	1.2079	-.37979
10	.783	1.103	.444	19.777	1.3184	-.47916

BIBLIOGRAPHY

1. Bowker, A.H. and G.J. Lieberman, Engineering Statistics, Prentice-Hall, Inc., (1959), Englewood Cliffs, N.J.
2. Box, G.E.P. and G.M. Jenkins, Time Series Analysis: Forecasting and Control, Holden Day, (1976), San Francisco.
3. Chow, G.C., "Tests of Equality Between Sets of Coefficients in Two Linear Regressions," Econometrica, Vol. 28, No. 3, (1960), 591-605.
4. Cook, T.D. and D.T. Campbell, Quasi-Experimentation: Design and Analysis Issues for Field Settings, Rand McNally College Publishing Company, (1979), Chicago.
5. Dixon, W.J. and M.B. Brown, Biomedical Computer Programs P-Series 1979, University of California Press, (1979), Los Angeles.
6. Fogel, L.J., Biotechnology: Concepts and Applications Prentice-Hall, (1963), Englewood Cliffs, N.J.
7. Hines, W.W. and D.C. Montgomery, Probability and Statistics in Engineering and Management Science, John Wiley & Sons, (1972), New York.
8. Kelley, C.R., "The Measurement of Tracking Proficiency," Human Factors, (1969), Vol. 11, No. 1, 43-64.
9. Lindgren, B.W., Statistical Theory, 3rd Edition, Macmillan Publishing Company, (1976), New York.
10. McCormick, E.J., Human Factors in Engineering Design, McGraw-Hill Book Company, (1976), New York.
11. Montgomery, D.C., Design and Analysis of Experiments, John Wiley & Sons, (1976), New York.
12. Montgomery, D.C. and L.A. Johnson, Forecasting and Time Series Analysis, McGraw-Hill Book Company, (1976), New York.
13. Poulton, E.C., Tracking Skill and Manual Control, Academic Press, (1974), New York.
14. Robinson, F.A., "A Study of Learning in the Operations of A Viscous Damped Traversing Unit," Thesis, Georgia Institute of Technology.

15. Sheridan, T.B. and W.R. Ferrell, Man-Machine Systems: Information, Control, and Decision Models of Human Performance, The MIT Press, (1974), Cambridge, Massachusetts.
16. Van Cott, H.P. and R.G. Kincade, Human Engineering Guide to Equipment Design, McGraw-Hill Book Company, (1972), New York.
17. Welford, A.T., Skilled Performance: Perceptual and Motor Skills, Scott, Foresman and Company, (1976), Glenview, Illinois.

